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Citation for published version:
Beckett, C & Augarde, CE 2011, 'Structure creation in earthen construction materials: information from dry soil mixtures', *Frontiers of Structural and Civil Engineering*, vol. 5, no. 2, 151.
https://doi.org/10.1007/s11709-011-0109-7

Digital Object Identifier (DOI):
10.1007/s11709-011-0109-7

Link:
Link to publication record in Edinburgh Research Explorer

Document Version:
Peer reviewed version

Published In:
Frontiers of Structural and Civil Engineering

Structure creation in earthen construction materials: information from dry soil mixtures

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Abstract

There is increasing interest in the use of earthen construction materials, such as rammed earth, due to their inherent sustainability. These materials have been used by man for thousands of years and some of the earliest examples can be found in China. Features of the structures of these materials arise from the means of production. In particular, *in situ* earthen construction materials exhibit strong anisotropy due to their layered nature. A more subtle structure effect arises from the way that the earth mixture is deposited. This paper reviews and discusses stratification effects in dry soil mixtures, including some original experimental work, and indicates some links between the features of the dry mixtures and earthen construction materials. Improved understanding of the physical processes in play will allow more accurate specification of these materials in the future, and hence spread their use.

Keywords: Rammed earth, stratification, particle size distribution, pore size distribution.

Introduction

"Rammed earth" (RE) is both a material and an earthen construction technique where a moist sandy-loam subsoil is placed between formwork and compacted (either manually or by using mechanised processes) into layers of roughly 100 mm depth. Once filled, the formwork is stripped, allowing the compacted soil to dry (**????**). RE is a technique that therefore does not require an advanced technological capacity in order to be used, as it relies heavily on local materials and simple (but physical) labour. Some of the earliest examples of RE construction, dating from around

2000 BCE, can be found in Xi'an and Taosi in eastern China, whilst the earliest European examples are Phoenician structures dating from between 1200 and 539 BCE (?). Trade and migrations of various peoples have meant that now there are examples of monumental and vernacular RE structures on every continent in the world, mostly existing in a wide band centred on the equator but more generally being found wherever resources are available and arid conditions, which are necessary for durability, exist (??). For more information on the chronology and the development of the RE technique, the reader is referred to ?.

The advent of modern construction materials, for example fired bricks and concrete, has led to a transition away from traditional earth building techniques in many areas where earth building used to be prevalent. Unfortunately, this shift, added to a loss of the traditional skills required to maintain earthen structures, has led to the degradation of existing structures and the perception of earthen structures as being sub-standard, relegating their use to projects such as disaster relief and emergency housing (?). At the other extreme, where earth building has survived, construction methods have been modified to use energy-intensive processes, increasing the financial and environmental cost of the structure and relegating the material to niche markets (?).

Recently, however, the sustainability and economic benefits offered by these materials have led to a renaissance for earthen construction techniques (????). In addition to the sustainable nature of the material, local sourcing of resources and the avoidance of the need to use cement (thereby significantly reducing the amount of CO_2 released per unit length of wall (?)), earthen structures are able to 'breathe', resulting in comfortable internal living environments throughout the year and negating the need for artificial ventilation (?). This is due to the need for RE walls to be thick (over 300 mm) in order to support applied building loads, granting them a good ability to absorb and retain heat during daylight hours which can be released as external temperature drops (??). Added to this are the naturally hygroscopic properties of the clay present in RE soil mixes (i.e. it readily absorbs or releases water, depending on atmospheric conditions) which result in a humidity of between 40 and 60% inside the structure (?).

It has been the tendency in the past to treat traditional earthen construction as a form of masonry, where design was based on heuristics and experience (?). However, the desire to use earthen materials in more varied applications has led to the need to consider them in more scientific terms. One current view is of these materials being *manufactured unsaturated soils*, such that their properties and behaviour should be determinable through the application of unsaturated soil mechanics principles. Using this approach, it can be seen that the strength of an RE component is controlled by a number of factors including the clay content (????), water content (????), interparticle friction and angularity (?), suction (?????) and the properties of the particle surfaces which are in contact or in near contact (???). These factors can all be related to the soil microstructure, namely the soil pore– and particle size distributions and the distribution of water within the voids, to name three primary properties (???????). In order to investigate the behaviour of RE specimens, therefore, it is necessary to be able to carefully control these properties. A method to achieve this, proposed by ?, is to create RE soil mixes out of dry constituent parts (silty clay, fine– and coarse sand and gravel) and to then add water to the desired water content. However, although this guarantees a known particle size distribution, it is necessary to determine whether or not the constituents will interact in a way as to impart some form of undesired structure on the resulting RE specimen, for example a layering of similarly-sized particles and the subsequent creation of a band of weakness due to larger pore spaces and poorer interparticle bonding. The focus of this paper is to link findings concerning the development of structure in dry soil mixtures to likely structural formations in earthen construction materials built *in situ*. In the latter the structure will have a significant effect on intrinsic properties such as shear strength.

Sandpile formation and phenomena of granular flow

Sandpile formation

If a sand of species X is poured into a silo, then a characteristically-shaped sandpile will form as shown in Figure 1. The central, linear section of the slope lies at θ_X, the repose angle for species X (which is equal to the friction angle if the sand is a Coulombic material, (**?**)), whilst the tail of the slope adopts an exponentially-decaying profile due to particles losing energy as they strike the silo base (**??????**). It has been shown experimentally that the shape of the sandpile tail is affected by the particle drop height and flow rate; the greater the drop height and flow rate, the greater the particle energy and so the longer it takes for the energy to dissipate through collisions (**??**).

Segregation and stratification

Segregation is the phenomenon whereby a mixture of two sands spontaneously separate into two distinct regions on pouring. Such a pattern is shown in Figure 2(a). Segregation can be understood as the conflict between two competing effects: size segregation is where larger grains can roll more easily over smaller grains than smaller over larger, leading to a segregated pile with small grains at the top and large grains at the base; and shape segregation, where grains are of equal size but different shapes resulting in the rougher grains being at the top of the pile and the smoother at the bottom (**?**).

If the larger grains are rougher than the smaller, therefore, the above two effects will compete, leading to stratification, where alternating layers of small and large particles are formed parallel to the surface of the sand pile with the smaller particles underlying the larger (**?**). An example of a stratification pattern is shown in Figure 2(b). Stratification has also been identified in mixtures of more than two species, where the parallel layers are formed with the smallest (which are necessarily also the smoothest) particles on the bottom of the layer, with progressively rougher particles lying on top (**?**). As can be seen in Figure 2(b), an initial segregation regime exists in the bottom corner of the sandpile prior to the stratification zone; only size segregation is active in this initial zone, such that the larger particles are at the base of the pile (**?**).

Effect of repose angle

To understand stratification, a 'microscopic' definition of the repose angles between the two sand species is required, showing the interactions between the individual grains (**?**). There are four generalised angles of repose, shown in Figure 3. In this formalism, the smaller species is denoted as "1" and the larger as "2". ϕ' is the friction angle of a single granular species, whilst θ_{xx} and θ_{xy} are the repose angles for single species or a combination of two species respectively, with species x rolling down a surface of species y. The need to define both ϕ' and θ_{xx} for a material is because ϕ' can be considered a material property whilst the repose angle is affected by external influences as will be discussed in the following sections.

It can be assumed that $\theta_{21} < \theta_{11} < \theta_{22} < \theta_{12}$ (**??**), as the repose angle for a small grain rolling down a slope of large grains must be larger than for the opposite case. By defining the repose angles in this manner, both size and shape segregation are included ($\theta_{11} < \theta_{22}$ is due to the shapes of the species, $\theta_{21} < \theta_{12}$ is due to the sizes) (**?**). According to **?**, the control parameter for the stratification-segregation transition is the difference between the friction angles of the pure species

$$\delta = \phi'_2 - \phi'_1. \tag{1}$$

If $\delta > 0$ then stratification will occur (**?**), otherwise the species will segregate. In addition, if the sizes of the two species are almost equal then segregation will only be partial ("continuous segregation", **?**).

Capture, percolation and amplification

Three main mechanisms are present in determining stratification: "capture"; "percolation"; and "amplification" (**??**). Both occur in the "rolling phase", where grains are in motion during an avalanche.

Capture is the trapping of rolling grains on the surface of the sandpile. As such, it is the smaller grains that are mostly affected, as they are the most sensitive to surface fluctuations.

Percolation is the effect of small grains filtering through the larger grains in the rolling phase, provided that the rolling phase is "thick" (five grains deep or more), (**?**). A large size ratio is necessary in order for percolation to function; in this case, a size ratio of 1.5 is recommended, below which the size segregation effect is very weak and the instability leading to stratification is not possible (**?**).

Amplification is the process of static grains on the sandpile surface becoming part of the rolling phase due to particle collisions. Amplification processes are of negligible importance if percolation is present as the small-grained rolling sublayer is in contact with a mostly large-grained static surface layer (**?**). As a result, amplification is restricted to thin flow conditions. "Cross-amplification" is the amplifying of one species of particle by a collision with a particle from its own or another species. An effect of cross amplification is that stratification does not stop when $\delta = 0$, but at some critical value $\delta_c < 0$, as smaller grains can roll over larger ones without being captured. However, the stratification is much weaker than when $\delta > 0$ (?).

Mechanism of layer formation

The dynamical process of layer formation can be divided into three stages: the avalanche of grains down the slope and the size segregation in the rolling phase due to percolation; the formation of a "kink"; and the uphill motion of the kink, with the formation of the dual-stratification layer (?).

Prior to an avalanche forming, the surface of the sandpile comprises mostly larger grains. When an incoming mass of grains avalanches down the sandpile, the small grains are captured whilst the large grains reach the base of the pile (?) so that the larger particles form the avalanche head. These larger particles form the initial stages of the kink (?). Further flow continues to "smooth" the sandpile surface (without affecting the slope angle) until the smaller particles reach the base of the sandpile. The small grains stop as they reach the kink due to their increased ease of capture, followed by the larger grains, resulting in the stratification pattern of a layer of small grains underlying a layer of large grains. The kink moves up the slope with a constant shape as more material is added, with the process repeating as the kink reaches the top of the sandpile (?). The process of kink formation and propagation is shown in Figure 4. The wavelength of the stratification layers is proportional to the thickness of the rolling layer and so to the grain flow rate (?). However, if the flow rate is too great then the kink mechanism is overwhelmed and the stratification pattern is replaced with mixing or weak segregation (?).

In a wide silo an avalanche might not contain sufficient mass to form a continuous layer reaching the silo base; instead, the avalanche halts partway down the sandpile, forming a "trapped kink", with a coarse wedge at its head and the characteristic stratification pattern behind it. The upslope kink mechanism reinitiates once an avalanche reaches the silo base (?).

Laboratory results

Having reviewed some of the literature in the area we now describe experimental work carried out to study some of the aspects discussed above.

Material selection

Fine– (average particle size 200μm, $\phi'_{peak} = 26.0°$, $\phi'_{ult} = 24.6°$, $\theta_{11} = 33.1°$) and coarse sand (average particle size 800μm, $\phi'_{peak} = \phi'_{ult} = 35.1°$, $\theta_{22} = 32.4°$) of particle gradings given in Figure 5 were selected as both being suitable for inclusion in an RE mix and for stratification investigations ($\delta > 0$ using Equation 1). Repose angle values were determined experimentally using the repose angles of free piles of the single species (i.e. no edge effects were present). Clay particles were not included as they would coat the sand particles and thereby mask any patterns formed. Whether their presence would counteract the formation of any segregation or stratification patterns is not discussed in this paper. The test chamber used in these experiments (referred hereafter as the "silo") was of dimensions 898 mm long by 446 mm high by 77 mm wide and was cleaned with an anti-static cleaner prior to each pouring experiment.

A relationship for determining the required width of a silo in order to prevent the walls affecting the slope repose angle is given in **?** as

$$\theta(d) = \theta_\infty \left(1 + e^{\frac{-d}{d^*}}\right) \tag{2}$$

where d is the silo width and d^* the "characteristic length" which is a function of the particle size. It should be noted that Equation 2 originally appeared in **?** with an error (the second term in the bracketed expression was subtracted instead of added as above). Using results presented in **?** and assuming a linear relationship between d^* and average particle size, $d^* \approx 27$ mm for coarse sand and 10 mm for fine sand, suggesting that the repose angles found using the above-mentioned silo are free of wall effects. The gravel used in an RE mix for specimen production is sieved to contain particles smaller than 10 mm to reduce the influence of large particles on structural behaviour (**?**); after sieving, the gravel investigated had an average particle size of roughly 6 mm, corresponding to $d^* = 175$ mm. It was therefore decided not to include gravel in the testing as the silo size (> 350 mm) and amount of material required were deemed unrealistic.

Effect of pouring direction

Results from pouring from several directions using a constant particle flow rate (manually controlled using a large scoop) were compared in order to determine whether the direction of pouring influences the resulting segregation or stratification patterns. The pouring directions (PDs) used are shown in Figure 6 and results in Figure 7. It can be seen that the stratification pattern initiates much closer to the silo wall for PD1 than for PD2 (Figure 7 (a) and (b)); this is because the initial slope can form much closer to the silo corner for PD1. It can also be seen that the initial pattern arising from PD2 is rounded; this is because of the initial pile not being close to the wall. As additional grains fill the gap between the initial pile and the wall, the stratification pattern becomes similar to that arising from PD1. Tests were conducted using PDs 4 and 5 to determine whether the shape of the initial pile influenced the stratification pattern (Figure 7 (c) and (d)). The general patterns obtained from PDs 4 and 5 can be described as the formation of an initial pile, the tip of which moves towards the grain source as the sandpile height increases. The stratification patterns are very similar (but mirrored) for both PDs, as would be expected. The final repose angle for all of the tests conducted was $32.2° \pm 0.8°$, i.e. very similar to the average repose– (32.8°) and friction angles (29.9°) for the two species (although the friction angles for the two species should not strictly be combined in this manner as it assumes that there are no additional species interaction effects). The similarity between the average single-species and combined-species repose angles suggests that edge effects were not significant, supporting the linear approximation derived from data given in **?**.

Variations in the stratification pattern with height are due to changes in the particle drop heights. As the drop height reduces, the inclination of the sandpile should approach the combined repose angle of the two species and the tail should shrink as the initial energy of the particles reduces, as seen in Figure 7 (a) and (b) (**??**). Results in Figure 7 also show that both stratification and segregation are present; this is due to the non-uniform particle sizes of the two species (i.e. for some particle combinations a size ratio of > 1.5 is not possible) and reducing particle energy as particles near the base of the sandpile. Therefore, although the average particle sizes and friction angles suggest that stratification should occur, results resemble a combination of patterns arising in the "continuous segregation" and "stratification" regions of Figure 3 of **?**.

Effect of particle flow rate

It was found that material left the scoop via an avalanche mechanism as it was tilted, suggesting that material was stratifying in the scoop prior to being introduced to the silo and making control of the flow rate difficult. The scoop was therefore substituted for a mechanical funnel in order to determine the effect of flow rate on the stratification pattern, using PDs 3 and 6 (as the cone drops material vertically).

Flow rates of 3.3×10^{-2} ls^{-1} and 6.4×10^{-3} ls^{-1}, corresponding to the funnel being fully– and half open respectively, were used and results are shown in Figure 8. The stratification pattern initiates much earlier (i.e. deeper) in the sandpile formation for both of the tested flow rates than for those sandpiles formed using manual pouring; this is likely due to an increased flow rate, combined with the vertical pouring direction, forming a steeper cone on impacting the silo base which immediately initiates the kink/trapped kink stratification mechanisms. The depth of the fine sublayer reduces with increasing flow rate due to an overwhelming of the percolation mechanism; the rolling layer is thicker and so fewer fine particles can percolate through successfully. The resulting repose angles were $31.6° \pm 0.3°$ for 3.3×10^{-2} ls^{-1} and $32.0° \pm 0.7°$ for 6.4×10^{-3} ls^{-1}. As the error bands for each flow rate overlap, it is not possible to determine whether the flow rate effected the combined repose angle, however results from **??** and the general similarity of all repose angles found during this investigation suggests that flow rate does not affect the repose angle. Again, Figure 8 shows that both stratification and segregation are present in the sandpile; this is also assumed to be due to the non-uniform particle sizes of the two species.

Stratification in a large silo due to draining was investigated in **?**. To test whether stratification was occurring in the funnel (and hence a structure being imparted to the material prior to the formation of the sandpile) the material in the funnel was allowed to drain entirely and sandpile formation cease, before being reinitiated. The resulting stratification patterns given in Figure 9 clearly show a band of coarse material delineating where the flow ceased and restarted, suggesting that stratification does occur within the funnel. To avoid this, material was continually added to the funnel until the end of each test.

Conclusions

The experimental work described above provides some insight into structure formation mechanisms in dry granular soil mixtures. Several general observations can be made:

- It has been determined that neither the flow rate nor the pouring direction influences the sandpile repose angle, the former supporting results found in **?**, **?** and **?**.
- The presence of both segregation and stratification observed at the end of all of the tests suggests that a simple check on material friction angles in non-uniform particle size materials is not sufficient to determine whether segregation or stratification will occur. The final repose angle might be the average of the repose angles of the constituent species, however the use of the average friction angle should be avoided. The resulting patterns are different to the "continuous segregation" region given in **?**, suggesting that a more gradual transition between segregation and stratification patterns exists.
- Segregation and stratification will occur within hoppers that are used to feed pouring experiments, confirming findings given in **?**. Therefore, it is necessary to ensure that these hoppers do not empty before the sandpile is fully formed.

Although it is admitted that the testing of only two components of an RE mix cannot describe the behaviour of the whole mixture, and the effect of water in the RE mix will, of course, be significant, these results indicate that if one wishes to maintain a consistent material structure for RE (or other *in situ* earthen construction material) one must be aware that the choice of the dry raw materials and the methods used to combine them will have an effect on the structural properties and behaviour of the material. In these unsaturated soils, this is of particular importance as the soil structure (e.g. the pore size distribution) is the key source of the soil's water retention, permeability and compressive and tensile strength properties.

Acknowledgements

The author is funded by a studentship awarded by the School of Engineering and Computing Sciences, Durham University.

References

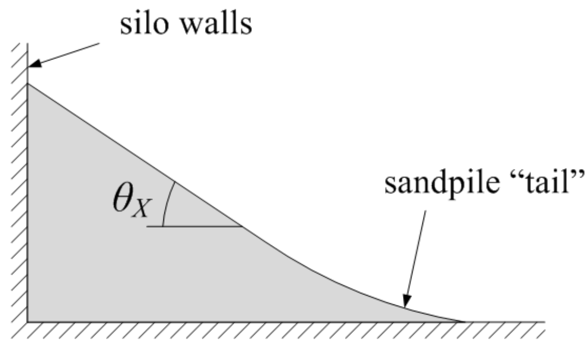

Figure 1: Typical shape of a sandpile. θ_{xx} is the repose angle of species x.

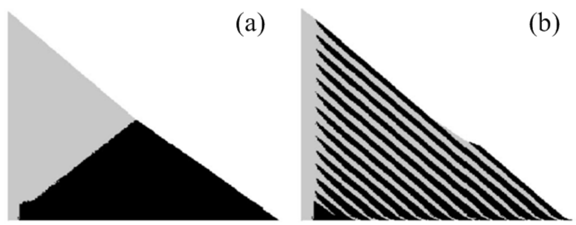

Figure 2: (a) Results for spontaneous stratification of a bidisperse mixture of smaller smooth grains (light) and larger rougher grains (dark). (b) Results for a segregating mixture of smaller rougher (light) grains and larger, smoother grains (dark) (**?**)

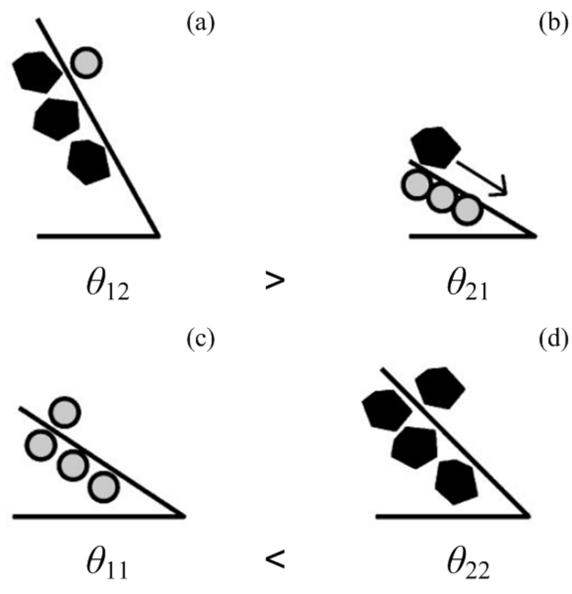

Figure 3: The generalised repose angles for: (a) small, smooth particle rolling down a surface of rough particles, θ_{12}; (b) rough, large particle rolling down a surface of small, smooth particles, θ_{21}; (c) small, smooth particle rolling down a slope of the same species, θ_{11}; (d) large, rough particle rolling down a slope of the same species, θ_{22} (**?**)

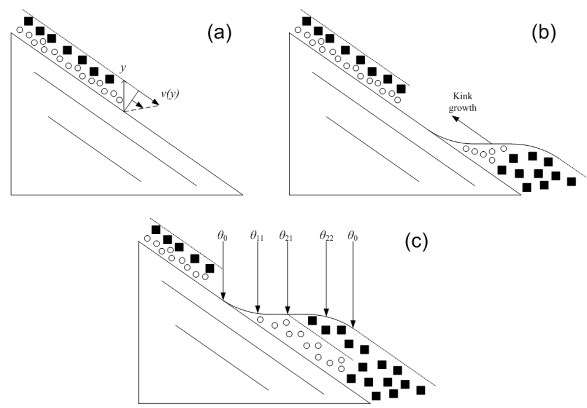

Figure 4: Diagrammatic process of kink formation and propagation (after ?): (a) initial avalanche at velocity $v(y)$; (b) formation of the kink; (c) profile and propagation of the kink up the sandpile (slope angle θ_0) with kink angles θ_{11}, θ_{21} and θ_{22}

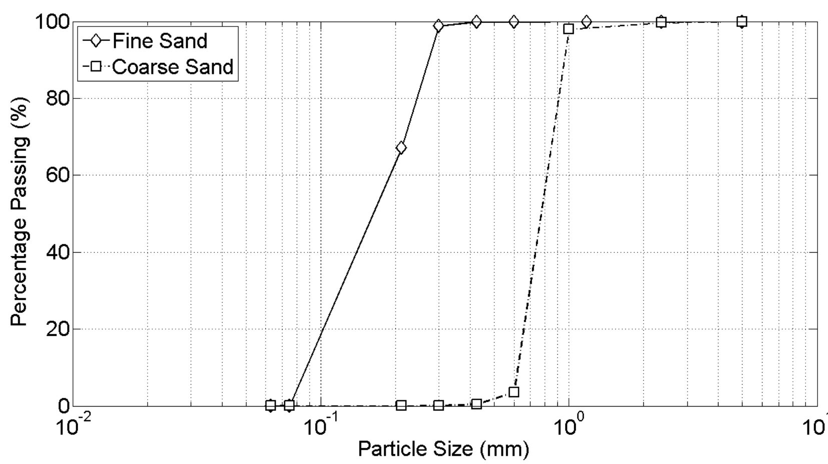

Figure 5: Particle grading curves for fine and coarse sand

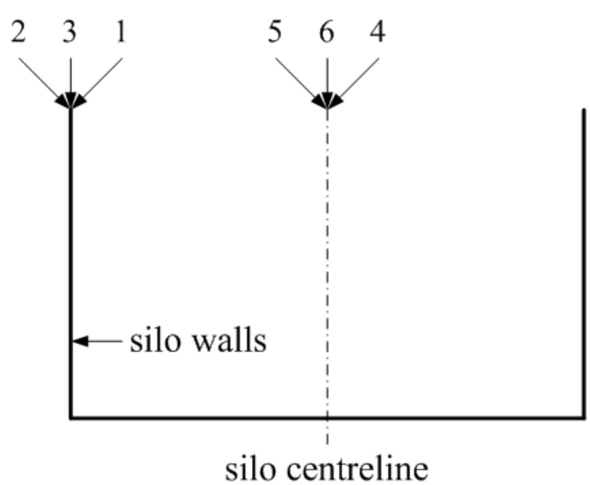

Figure 6: Silo pouring directions

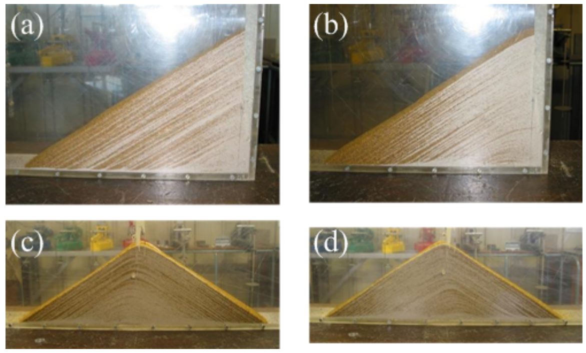

Figure 7: (a)-(d) Stratification results for PDs 1, 2, 4 and 5 respectively (all using manual pouring)

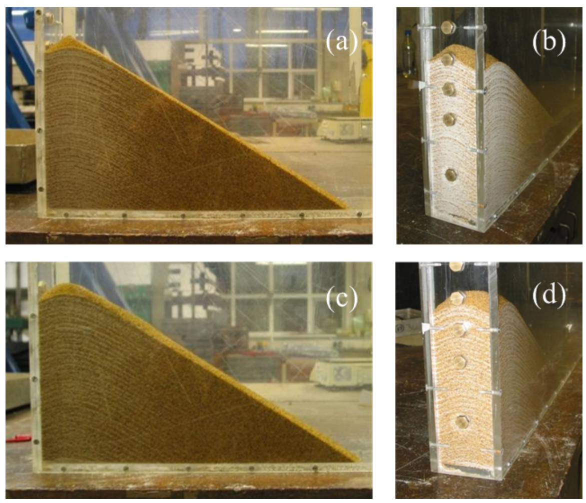

Figure 8: (a)-(b) Stratification pattern for low flow rate; (c)-(d) Stratification pattern for high flow rate

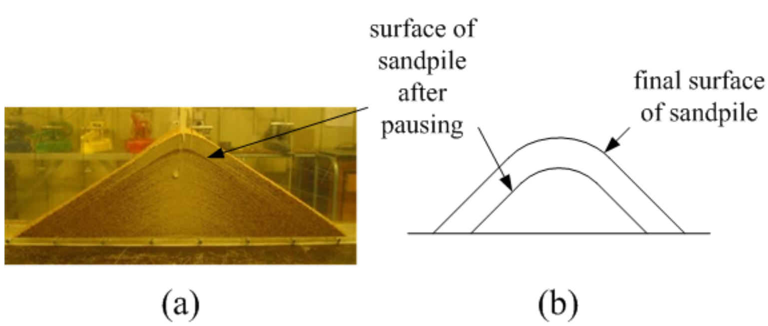

Figure 9: (a) Stratification pattern showing delineation between pouring phase; (b) Diagrammatic description